A Compton Gamma Imager for Criminal and National Security Investigation

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DRDC-RDDC-2014-C104
May 2014

CRTI 07-0193RD

IMPORTANT INFORMATIVE STATEMENTS

CRTI 07-0193RD A COMPTON GAMMA IMAGER FOR CRIMINAL AND NATIONAL SECURITY INVESTIGATION was supported by the Canadian Safety and Security Program (CSSP) which is led by Defence Research and Development Canada's Centre for Security Science, in partnership with Public Safety Canada. Partners in the project include National Research Council, McGill University, Royal Canadian Mounted Police, Public Safety Canada, Toronto Police, and Canada Border Services Agency. CSSP is a federally-funded program to strengthen Canada's ability to anticipate, prevent/mitigate, prepare for, respond to, and recover from natural disasters, serious accidents, crime and terrorism through the convergence of science and technology with policy, operations and intelligence

Abstract

Law enforcement agencies, first responders, and others collecting information in an emergency involving the release of radioactivity, require instrumentation which can quickly and intuitively show them the location of the sources of radiation. Responding to this need, project partners designed Compton gamma imagers, which can show the location of a radiation emitter on an optical photograph. The group pursued two designs with different risk profiles and advantages: a "bar" design based on long bars of scintillator read out at the ends with conventional vacuum photomultiplier tubes and a "pixel" detector based on small cubes of scintillator each read out with a novel silicon photomultiplier. After an extensive design and optimization process involving simulation as well as test-bench validation, laboratory demonstration units were designed, and assembled. Both the bar and pixel prototypes function well, providing an image resolution of better than a degree within a minute of data taking for a 10 mCi Cs-137 source 40 m away. If these prototypes could be ruggedized and brought to market, they would provide an enormous improvement in capability to teams responsible for localizing radiation emitters in a radiological emergency.

Résumé

Les autorités policières, les premiers intervenants, et les autres autorités responsables d'accumuler de l'information lors d'une urgence impliquant la présence de radioactivité, ont besoin d'appareils pouvant rapidement et intuitivement indiquer l'emplacement des sources de radiation. En réponse à ce besoin, les partenaires du projet ont conçu des systèmes d'imagerie gamma par diffusion Compton, qui peuvent indiquer la localisation d'un émetteur de radiation sur une photographie optique. Le groupe a poursuivi deux concepts présentant des profils de risque et des avantages distincts: un concept à « barre », qui est basé sur l'utilisation de longues barres de scintillateur où le signal est recueilli aux extrémités avec les tubes photomultiplicateurs à vide conventionnels, et un concept à « pixel », basé sur l'utilisation de petits scintillateurs cubiques, où le signal de chacun est recueilli avec des photomultiplicateurs silicium novateurs. Après un processus élaboré de conception et d'optimisation comportant la simulation aussi bien que la validation expérimentale, des appareils de démonstration de laboratoire ont été conçus et assemblés. Les prototypes à barre et à pixel fonctionnent bien tous les deux, et fournissent une image d'une résolution d'image supérieure à un degré pour une minute d'acquisition de données pour une émetteur Cs-137 de 10 mCi à 40 m du détecteur. En rendant ces prototypes robustes pour déploiement, et en les commercialisant, ils contribueront grandement à l'amélioration des capacités des équipes d'intervenant responsables de localiser les émetteurs de radiation lors d'une urgence radiologique.

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Acknowledgements

This work was supported by Defence Research and Development Canada Centre for Security Science Chemical, Biological, Radiological/Nuclear, and Explosives Research and Technology Initiative (CRTI 07-0193RD).

1 Introduction

A gamma imager is a device which can determine the locations of gamma emitters and present this as an image – often overlaid on a conventional optical photograph [1]. Gamma imagers have been used extensively in medical physics [2][3][4] and have also been deployed on satellites to image galactic and extragalactic sources of gamma radiation [5]. As of the time of submitting the project proposal for CRTI 07-0193RD, a few groups around the world had developed gamma imagers also for use in safety – to image radioactive spills at a power plant, for instance [6][7], and for use in treaty verification – a non-obtrusive method of inspecting nuclear weapons [8]. Work on the development of gamma imagers for the particular needs of security agencies was, however, very new [9][10].

Canada has particular constraints in its operating environment due to the vast area of the country over which resources must be made available on restricted budgets, and due to the, at times, harsh exterior environmental conditions. For these reasons, it was felt necessary to develop a gamma imager particularly designed for the needs of Canadian investigators and responders.

At Natural Resources Canada (NRCan), within the Nuclear Emergency Response (NER) group, tremendous experience exists in conducting radiometric field surveys. As well, the group has training and experience in particle physics and in medical physics. Additional expertise in particle physics, including particle astrophysics, was drawn on from the National Research Council, and from McGill University. These scientists judged that a Compton gamma imager, a particular type of gamma imager well suited to detection of threat isotopes, made out of solid scintillator, would be ideal for the Canadian operating environment. As of the time of the project proposal, simulations of a Compton gamma imager for use in safety and security had progressed to the point that it seemed probable that a reasonably rugged and transportable device could deliver an image with better than a degree image resolution in a field of view of 45□ by 45□, for a 10 mCi Cs-137 source situated 40 m away, in under a minute. This became our design aim.

2 Purpose

This project supports the specific priorities identified by the Chemical Biological Radiological/Nuclear and Explosives Research and Technology Initiative (CRTI) in the 2007-2008 Call for Proposals in the area of criminal and national security investigation capabilities. As stated therein, there is a need for innovative detection technologies to assist investigators in intelligence gathering pre- and post-incident. To address this need, this project built and demonstrated Compton gamma imagers which show the locations of radioactivity, overlaid on a photograph of the environment.

The capabilities identified as gaps which were targeted by this project included: operational usefulness, stand-off distances greater than metres, portability, conceal ability, sensitivity, speed, accuracy and suitability for robotic platforms.

The project also pertains to priorities identified in the Sept. 2012 Call for Proposals issued by the Canadian Safety and Security Program (CSSP). The Compton gamma imager is an excellent screening technology for rapid detection and identification of radiological threats, addressing Priority P1.6 and intermediate outcome 5. Also, intermediate outcomes 1 and 2 are relevant. Knowledge of such emerging technologies is essential for adequate science and technology advice to feed into emergency management policies and action plans. Also, public safety and security practitioners equipped with a gamma imager would certainly be at reduced risk.

3 Methodology

3.1 Compton Imaging

Responder and surveillance operators require instruments to localize radioactive substances which are quick and simple to use, and intuitive to interpret. For this reason, in this project we have designed an imager of radiation, which can produce an image of dispersed radioactivity overlaid on an optical photograph.

The basic principle of Compton imaging is to reconstruct both the energy, E_1, and the position, $\boldsymbol{x_1}$, of a gamma ray of energy E_γ, as it undergoes a Compton scatter within a detector, and then to record the energy, E_2, and position, $\boldsymbol{x_2}$, of the subsequent photo-absorption of the gamma ray. These quantities can be inserted into the Compton scattering expression to obtain the Compton scattering angle, θ_C,

$$\cos\theta_C = 1 + m_0 c^2 \left(\frac{1}{E_\gamma} - \frac{1}{E_2} \right), \text{ where } E_2 = E_\gamma - E_1 . \tag{1}$$

The emitter's location is thus constrained to lie somewhere on a cone-shaped locus of opening angle, θ_C, with axis defined by $\boldsymbol{x_2} - \boldsymbol{x_1}$. The location of the source may be then further constrained by overlaying several such "Compton cones".

A simple Compton imager consists of two components, the "scatter" detector, which measures E_1 and $\boldsymbol{x_1}$, and the "absorber" detector, which measures E_2 and $\boldsymbol{x_2}$. The challenge in building a Compton imager, is to develop a scatter detector which can give the energy and position of an interaction, without introducing dead material in the path of a gamma ray as it leaves the scatter detector to encounter the absorber detector.

Early studies optimized materials and geometries for the imager design [11][12][13]. The team then came up with two different approaches for building a position-sensitive detector without dead material in the way: the "bar" imager, and the "pixel" imager.

3.2 Bar Imager

The bar design is an innovative approach which places particular importance on the reduction of output channels to keep costs low. Scintillation light from the interaction of gamma radiation in the detector is collected at the two ends of long scintillator bars, using conventional photomultiplier tubes (PMTs). In this way, if sufficient position resolution can be realized, then a bar imager with only *2N* light collectors, could give comparable performance to a pixel imager with N^2 light collectors.

The position of interaction along the bar is reconstructed by comparing the relative amplitudes of the two light pulses collected. To achieve sufficient position resolution, the surface of the bar must be roughened – effectively increasing the attenuation of the optical light along the bar. This

process must be conducted in a very precise manner, such that the improvement in position resolution, with corresponding worsening of energy resolution, is balanced to obtain the shortest possible time-to-image. This work has been described in detail elsewhere [14].

One bar module from the final prototype bar imager is shown in Figure 1. The scintillator chosen was NaI(Tl). It is a hygroscopic material, encapsulated by the manufacturer in aluminum with two optical windows. Two PMTs are placed at the ends of the encapsulated crystal, and foam, springs, and a red exterior aluminum packaging provide additional mechanical support.

Figure 1: An example of one bar module from the absorber detector. The aluminum casing housing the NaI(Tl) crystal is seen in the centre. At each end are the PMTs for light collection, and cables for carrying the high voltage, and the electric pulse. Springs press the PMT against the crystal casing.

The full bar imager is shown in Figure 2, with ten bars in the scatter layer and seven larger bars in the absorber layer. The black cables at the ends provide high voltage to the PMTs, and conduct the signal from them. The rectilinear grey tubing and clear plastic sheet provide the mechanical support for the structure. More details on the assembly and performance of the bar imager can be found elsewhere [15].

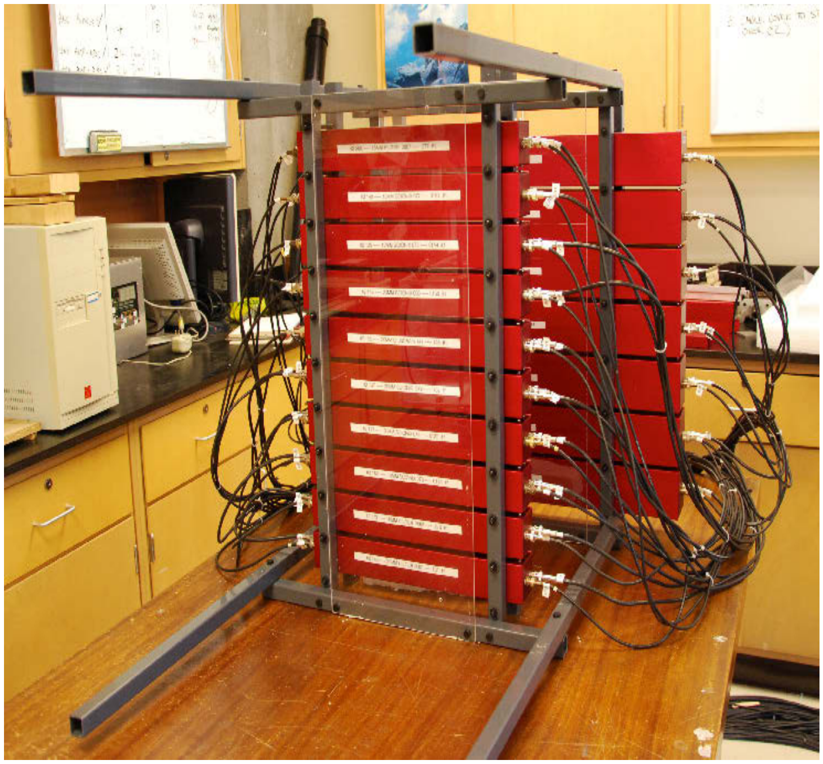

Figure 2: The fully-assembled bar-based imager. The red boxes are the exterior casing of the individual modules. The scatter and absorber layers are held in place with rectilinear grey plastic tubing. A transparent rigid plastic sheet on the front of the imager provides mechanical stability. Cables on the right and left of the bars transmit high voltage and signal output.

3.3 Pixel Imager

For the pixel design, light collection components known as SPMArrays were used in the scatter layers, rather than conventional PMTs. An SPMArray is a solid state device which can be made so thin and light, that the light collection from the scintillator can take place within the active volume of the imager, without introducing significant dead material. The advantage then of the pixel design is that it is not necessary to increase the attenuation of light in the scintillator in order to achieve adequate position resolution. A single pixel consists of a cubic crystal of scintillator mated to an SPMArray of matching size on one face. The position resolution is simply determined by the pixel size.

Figure 3 shows a single SPMArray.

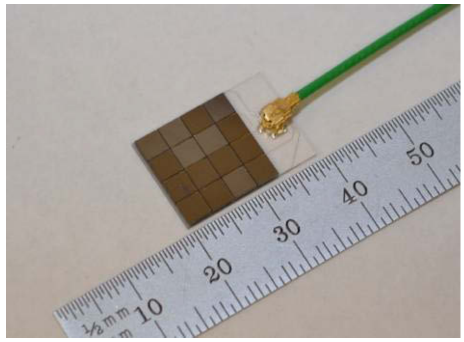

Figure 3: A single SPMArray. The sensitive area measures 1.35 cm x 1.35 cm and the total thickness of the device is 500 µm. Micro-coaxial cable carries the electric signal to the digitization electronics.

The pixel imager features two scatter layers, each with eighty-one CsI(Tl) scintillator crystals in a nine by nine array. The CsI(Tl) crystals are each mated to an SPMArray using optical gel, and this system is wrapped with plumber tape for light tightness. Figure 4 shows the inside of one scatter layer. The scatter-layer "pixels" appear white due to the plumber tape. The green cables, one for each pixel, conduct bias voltage and signal to and from the layer. The construction materials, a carbon fibre and Delrin frame, and foam positioning inserts to hold the pixels in place, were chosen to be as light as possible.

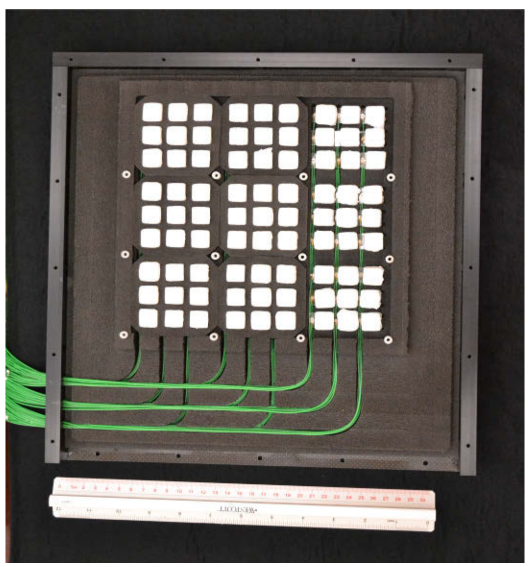

Figure 4: Inside of one scatter layer, showing the Delrin frame and foam insert. The eighty-one individual pixels of CsI(Tl) are shown, each affixed to its SPMArray (not visible) and wrapped in plumber tape. The green micro-coaxial power and signal cables can be seen exiting the layer to the lower left.

It is not critical for the absorber layer to have low-mass light collection, since the absorber layer is designed to fully absorb the scattered gamma ray, and the light collectors can be positioned on the back of the detector, out of the way. For the pixel imager, the absorber layer consists of NaI(Tl) crystals clad in aluminium and mated to conventional PMTs, in a 10 x 10 array of 100 crystals.

Figure 5 shows the full pixel imager. The absorber layer, at the rear, on the left in the figure, is held in place by an aluminium frame. Black cables from the rear of the imager convey the high voltage and signal to/from the absorber layer. One scatter layer is shown at the front, on the right in the figure. It is mounted on a motor which will allow for automatic adjustment of the inter-layer spacing. More details on the pixel imager have been published elsewhere [16].

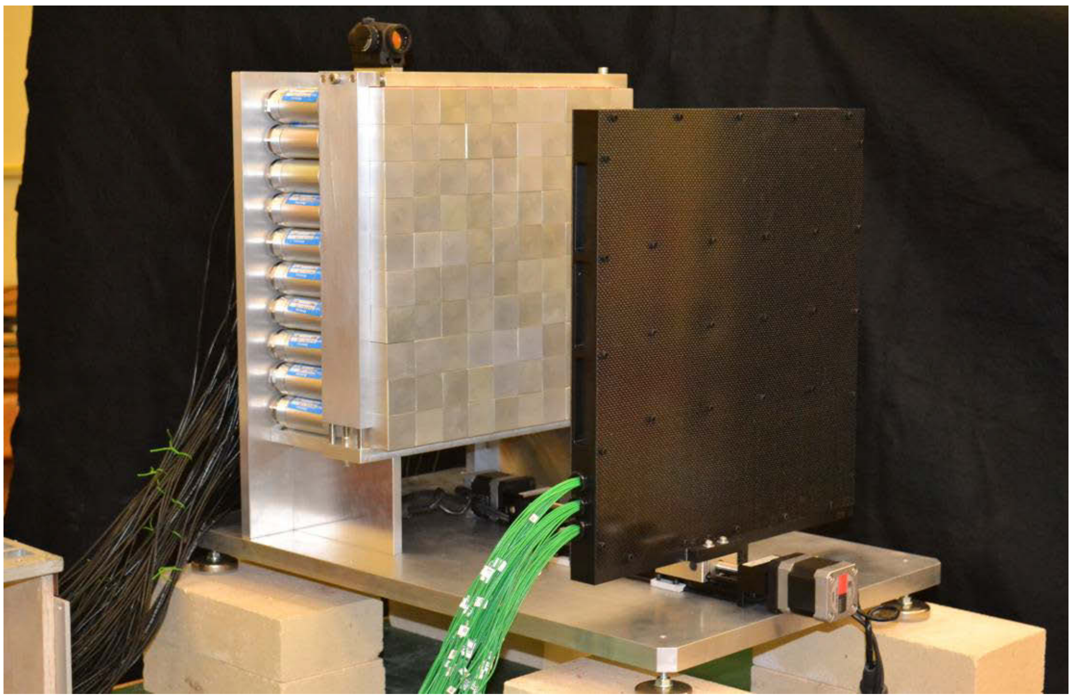

Figure 5: Full pixel imager with one scatter layer in place. The absorber layer is 100 NaI(Tl) + PMT "pixels" in a 10 x 10 array, held together in an aluminum frame. Black cables for signal and power are visible coming from the back of the absorber layer. A laser sight for alignment is affixed to the top of the absorber layer frame. The black Delrin and carbon fibre frame of the scatter layer is visible but the individual scatter layer pixels are not. The green signal and power cables from the scatter layer are visible, exiting the scatter layer at its lower left. The scatter layer is attached to a Velmex motor for eventual automated setting of the inter-layer distances.

4 Results

4.1 Image Reconstruction

To reconstruct the source location using a Compton imager, Compton “cones” with opening angle θ_C may be back-projected on to a hemisphere and the source location inferred from the places where the cones intersect. An example of such a “backprojection image” taken with the pixel detector is given in Figure 6. The image corresponds to only 1.8 seconds of data taking for a 1 mCi Cs-137 source about 10 m from the detector – and only about ten Compton cones have been reconstructed. Still, by entering the cones into a two-dimensional histogram, the intersection of the cones, where some pixels receive entries corresponding to more than one event, shows up clearly as the red area in the colour scale version of the image.

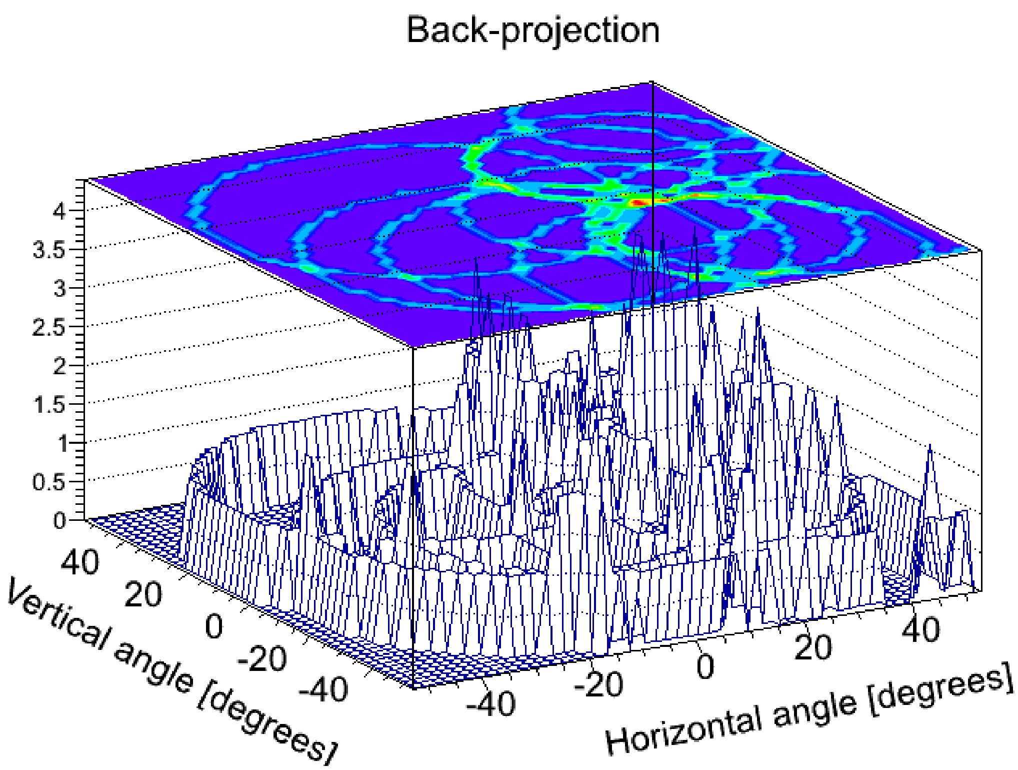

Figure 6: Example back-projection image using the pixel imager, for 1.8 seconds of data taking with a Cs-137 source at about 10 m from the imager.

To quantify the image resolution, a least-squares minimization has been applied to the back-projected cones, to find the direction in space which minimizes the sum of the angular distances of closest approach between that direction and each back-projected cone. The algorithm which has been developed to do this minimization is called GAmma Imaging Analysis (GAIA) and has been described elsewhere [16].

4.2 Bar Imager

The bar imager was developed, assembled and tested at McGill University in Montreal, before being transported to NRC in Ottawa, for further calibration, testing, and a series of demonstrations which were held from Nov 2012 to Feb 2013. Unfortunately, a manufacturer's error in engineering the optical window and the housing for the NaI(Tl) bars lead to breaking of the hermetic seal and subsequent performance loss for some of the bars. Therefore, the version of the bar imager which was demonstrated and for which results are shown here, included only four bar modules in the scatter layer, and 10 bars in the absorber layer.

Figure 7 shows a back-projection image of a Cs-137 source 10 m away, corresponding to one minute of data taking. To produce a clean overlay of the back projected cones on the optical image, contours are shown at different fixed percentages of the maximum bin occupancy in the two-dimensional back-projection histogram. The source is represented in the correct location.

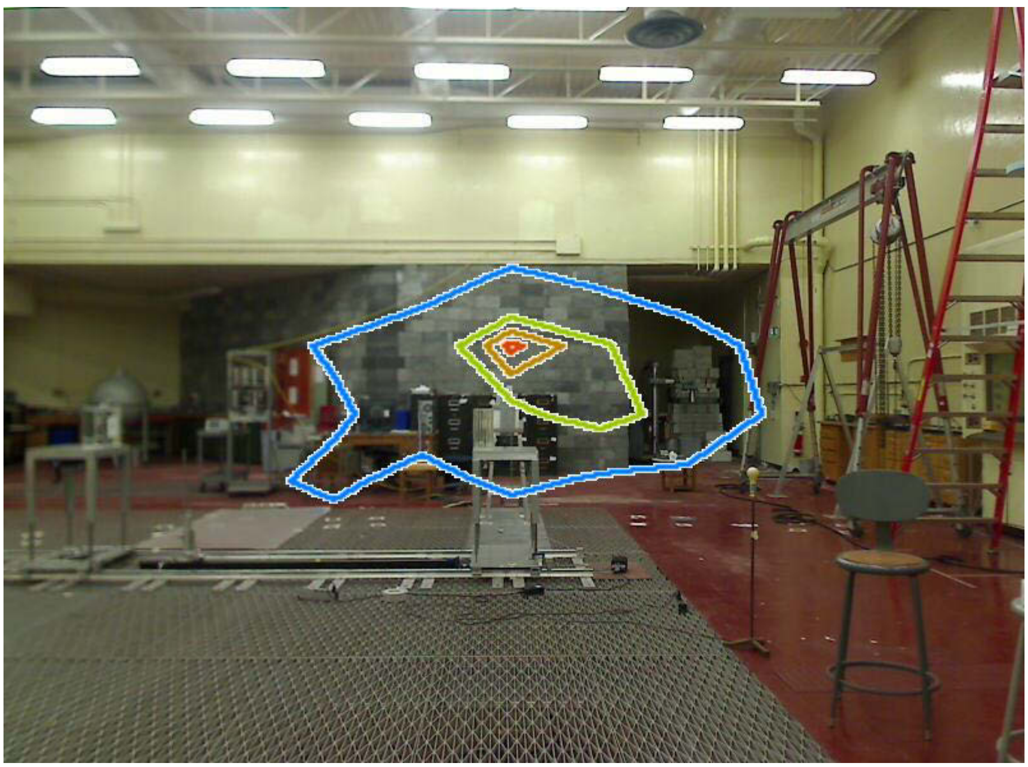

Figure 7: Back-projection image of a ~1 mCi Cs-137 source, corresponding to 60 seconds of data accumulation with the bar imager, and the source approximately 10 m away.

To fully quantify the time-to-image of the bar detector, the precise source position was reconstructed using the GAIA algorithm. It is then possible to determine the root-mean-square (RMS) deviation of the reconstructed source position over a number of samples of a certain acquisition time. These results are shown in Figure 8. Thus, for example, for a number of trials of 40 seconds length, there is a spread of about one degree in the resulting reconstructed source

positions. Alternately, we say that the “time-to-image” for a 1 mCi Cs-137 source at 10 m is about 40 seconds.

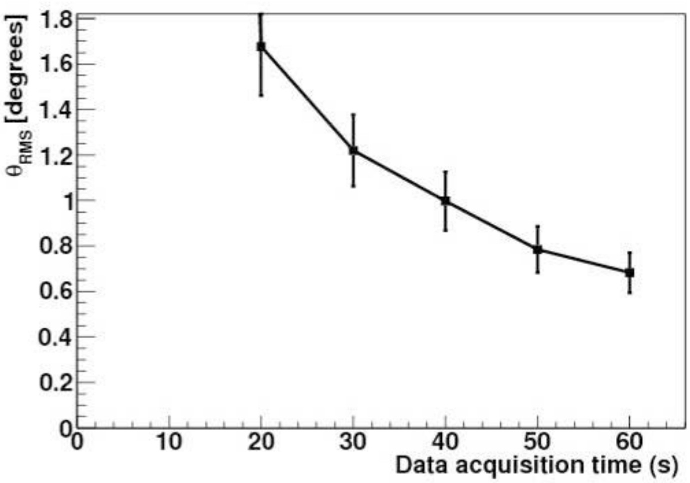

Figure 8: The RMS spread of the reconstructed angle from the source-detector axis to the symmetry axis of the detector is shown as a function of data acquisition time. The distribution shows the improvement in image resolution with longer acquisition time. An RMS resolution of better than one degree is achieved for acquisition times greater than about 40 seconds.

4.3 Pixel Imager

Figure 9 shows a simple back-projection contour image as obtained with the pixel detector. The pixel detector was outfitted with a very wide-angle optical camera which allows for the display of gamma images over a $\pm 53^\circ$-wide field of view. The wide-angle camera necessarily introduces distortions in the optical image, as can be clearly seen in the row of ceiling lighting in the image presented in Figure 9. Care must therefore be taken in the mapping of the gamma image onto the optical image. Nevertheless with a relatively simple first attempt at alignment of the two images, shown in Figure 9, a source is correctly localized.

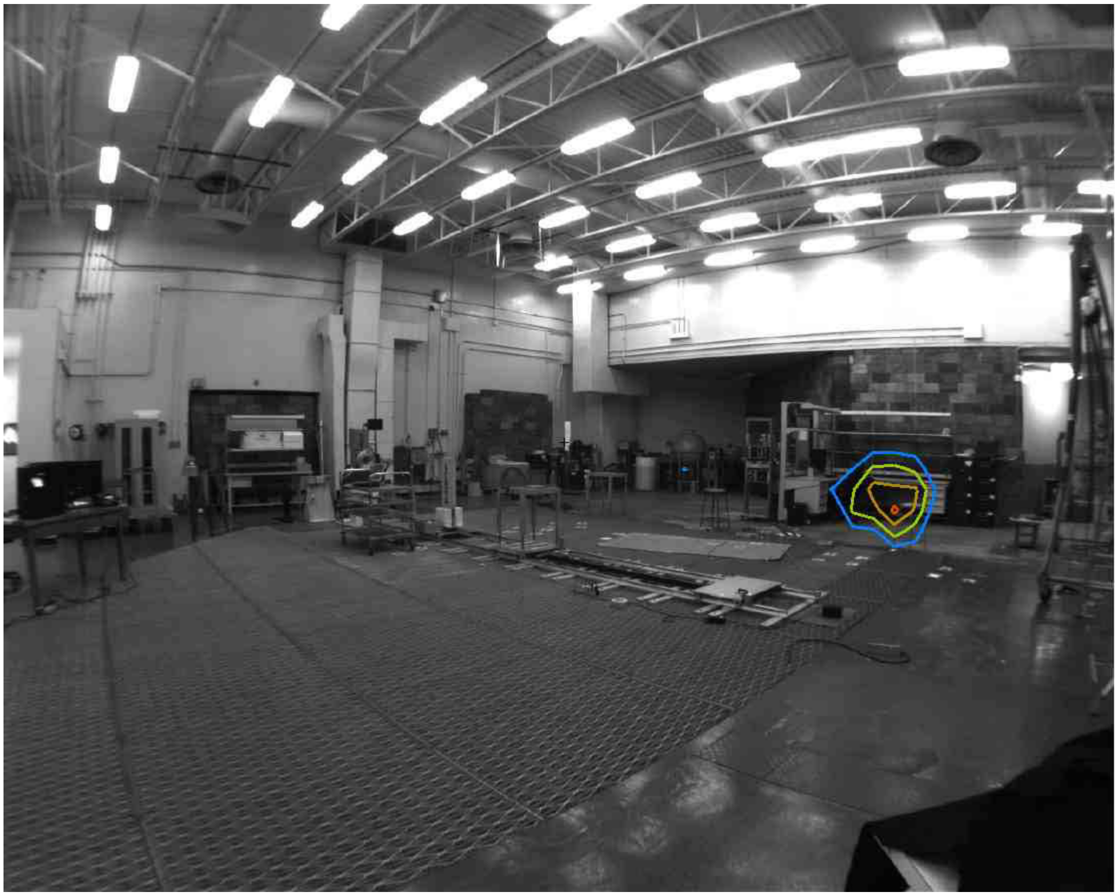

Figure 9: Back-projection image of a ~1 mCi Cs-137 source, corresponding to 2 minutes and 40 seconds of data accumulation with the pixel imager, and the source approximately 10 m away.

A gamma image using the GAIA fitting algorithm is presented in Figure 10 for an acquisition time of one minute. The reconstruction package is based on a more sophisticated algorithm which takes into account the different uncertainties of each detected event. It is thus able to tighten up the source localization as can be seen from the narrow contours.

Figure 10: Source image reconstructed using the GAIA algorithm from 60 seconds worth of data taking for a ~1 mCi Cs-137 source positioned about 10 m from the imager. The red, yellow and green contours show the one-, two-, and three-sigma confidence intervals respectively. The direction vector toward the source from the imager axis is thus reconstructed to within 0.4° at the one-sigma confidence level.

The RMS of the angle to the source as reconstructed using GAIA is shown in Figure 11 versus data acquisition time. We find that the pixel imager achieves an image resolution of better than one degree in less than 30 seconds of acquisition time.

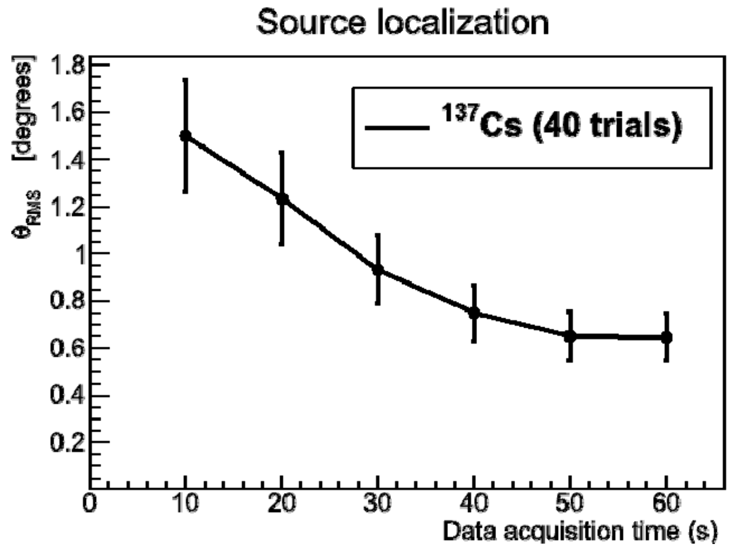

Figure 11: RMS resolution on reconstructed angle versus acquisition time. An angular resolution of less than one degree is achieved within thirty seconds.

5 Discussion

5.1 Bar versus pixel prototypes

The decision was made early in the project to invest in development of both the bar and pixel designs, to balance risk. It was not clear at the start of the project that a surface treatment could be developed for the desired overall imager size, which would be successful in producing a satisfactory position resolution while not severely impacting energy resolution. The pixel imager, on the other hand, was reliant on the emerging SiPM technology, which could well not have developed to the point of delivering adequate performance in the small form factor which was needed for this design.

In the end, both the bar and pixel laboratory prototypes satisfied our design aim. Extrapolating from the times to image obtained for a 1 mCi source at 10 m, we find that both designs would localize a 10 mCi Cs-137 source 40 m distant, to within one degree, within one minute of data acquisition.

To perform a detailed comparison of the performance of the two imagers, it would be necessary to rationalize their performance in terms of their eventual cost and portability, and with respect to their overall respective volumes. It is not possible to finalize this comparison within the scope of the current project.

5.2 Partnerships and Networks

CRTI 07-0193RD brought together McGill University, Natural Resources Canada, and the National Research Council, in a new scientific collaboration. Researchers, including a professor, a post-doctoral researcher, a graduate student, and government scientists, from these three institutes, worked together very well in a free exchange of ideas, of technical and scientific knowledge, and of reasoning. Throughout the project, the researchers met weekly via teleconference to exchange views on the week's scientific progress. Some laboratory equipment was also exchanged among the institutes in order to facilitate different stages of progress.

The scientific partnership has therefore been extremely valuable, and fruitful. The project leaves behind two working laboratory prototypes. The researchers will continue their scientific work with these instruments, and efforts are underway to bring a post-doctoral researcher and additional graduate students into the team. Thus, the team is continuing in knowledge generation and transfer to new researchers in the field.

Throughout the project implementation and execution, efforts have been made to involve potential end-users in steering the project outputs. The Royal Canadian Mounted Police (RCMP), Public Safety Canada (PS) and the Canadian Border Services Agency (CBSA) all have representatives as project partners. The opinion of these partners was solicited at crucial project design stages and their needs influenced, for example, the decision to develop two less-expensive prototypes rather than devoting the entire equipment budget to one extremely complex prototype.

Additionally, on Nov 15th, 2012, Nov 19th, 2012 and Mar 5th 2013, demonstrations of the gamma imagers were provided to representatives of the CSSP, Health Canada, DRDC, PS, CBSA, the RCMP, Carleton University, Radiation Solutions Inc., and additional representatives from the National Research Council, and Natural Resources Canada. The imagers were shown resolving source locations in real time for a variety of scenarios including finding single point sources of different energies, and localization of more than one isotope in the field of view, both of the same and of different gamma energies.

Interest in eventual deployment of the imagers, if they could be ruggedized and packaged compactly, has been expressed during regular project review committee meetings and again following the live demonstrations, by CBSA, by RCMP, and representatives of the NRCan Nuclear Emergency Response (NER) field team.

5.3 Impact

This project has had impact in a couple of different ways.

The science of Compton gamma imaging has been advanced through the work of the project team. The team has been accepted to present their work at international peer-reviewed conferences and has been successful in publishing their work in high impact journals (see Annex C). Notably, the Nuclear Instruments and Methods publication on the “First demonstration of a Compton gamma imager based on silicon photomultipliers” was one of 20 most-downloaded papers for that journal in the 90-day period following its publication. Additionally, a Ph.D. student in particle physics at McGill has completed her thesis work under the project. This puts her in a very small subset of those scientists applying physics techniques to safety and security, who actually received their training in the field.

Potential end-users are now, as a result of this project’s work, much better informed as to how Compton gamma imaging can aid their work and as to the state of the art in their development. The strongest impact, of actually creating safer environments for security personnel, responders, and ordinary Canadians, will not obtain until after the prototypes can be moved out of the laboratory and put into use.

6 Transition and Exploitation

6.1 Transition to End Users

The original impetus for developing the Compton imager arose out of the experience of the project lead in field exercises with the NRCan NER team. It was very clear that a gap existed in the ability of the federal response teams to support surveillance operations by providing the location of a radioactive source, particularly in urban environments, and when the search had to be conducted discretely, from the road. Thus, the NRCan NER team is active in the project, both as project manager and researchers, and as potential end users of the final product. A Compton gamma imager, fully ruggedized, fieldable and transportable, would certainly form an essential component of the NRCan NER team kit.

Both CBSA and RCMP have expressed throughout the project that a Compton gamma imager, once ruggedized and made compact enough for their platforms, would be worth an investment of funding.

DRDC-Ottawa has partnered with NRCan and NRC in a two-year follow-on project which will culminate in the production of specific recommendations for the deployment of a Compton gamma imager by the Canadian Forces [17][18].

The project team is thus very encouraged to continue to develop the Compton imagers, both in terms of the science involved in improving their capabilities, and in terms of the engineering and market research involved in getting them out the door.

6.2 Follow-on Development

6.2.1 Follow-on Research

Through the course of the project, the science of Compton imaging was advanced. The project team used simulation and test-bench studies to develop designs with the shortest possible time-to-image, given that the imager should a) consist of solid scintillator, proven to work well in field-deployed systems in the rugged Canadian environment and b) be of a certain maximum size which would allow for human transportability between platforms. The scientific work necessary to meet these aims has been achieved, nevertheless a number of open areas remain to be explored:

- Develop algorithms to reconstruct multiple, or extended sources
- Investigate three-dimensional imaging
- Image an object in motion, or image a stationary object from a platform in motion, e.g. imaging from an airborne platform

6.2.2 Follow-on Commercial Development

Although research is on-going to further understand and to improve the Compton imagers, the current laboratory prototypes are already developed to an extent that with an appropriate

engineering or commercial partner, they could suitably be packaged and commercialized for use by field teams.

Each design has particular engineering challenges which would have to be addressed. In the case of the pixel imager, in addition to some breakage of the SPMArrays occurring, it has been discovered that the active material of the SPMArray has been compromised by absorption of contaminants from the optical gel used to mate the SPMArray with the CsI(Tl) crystal. A more durable and properly sealed SPMArray would have to be utilised. Discussions with the supplier, SensL, are already underway on development of replacement SPMArrays with these characteristics.

In the case of the bar design, the crystal manufacture turned out to be challenging for the suppliers. A fraction of the bars has failed due to a) loss of the hermetic seal which protects the hygroscopic NaI(Tl) scintillator from humidity in the environment and b) the fragile nature of a long, thin bar. Some development work would have to take place to design a more effective housing for these crystals.

In addition, there is considerable engineering and development work which is common to the two designs:

- Implement gain stabilization
- Devise shock mounting to prevent breakage of crystals and components
- Develop custom electronics for
    - voltage supply
    - pulse amplification
    - pulse digization
- Develop exterior housing for
    - water resistance
    - temperature stability
- Make interface and packaging user friendly, including
    - simplified calibration
    - integration with Global Positioning System (GPS) measurements

6.3 Intellectual Property Disposition

The intellectual property agreement shall continue to follow that established in the project charter [20]. The most relevant of the clauses at project close-out is section 7.4 in which it is written, "In the case of Foreground IP that was created by employees of more than one partner, the partners shall own the rights in that Foreground IP in proportion to the contributions."

6.4 Public Information Recommendations

Compton imagers are being actively developed for security applications by a number of research groups around the world, which are openly publishing their research [9][10][21]. The work undertaken during this project is scientific in nature, providing a practical application of a concept which was published in 1974 [1], and taking incremental steps beyond the work of those other experimental groups. Most importantly, we do not lay out exact specifications or performance measures of an imager in use by security or armed forces. Therefore, the work done within the scope of this project does not need to be classified and may be released to the public.

7 Conclusion

Project CRTI 07-0193RD has been a success. The essential goal of the project was to design and build a gamma imager optimized for use by Canadian security and response teams. Already, prior to project inception, simulations of a Compton gamma imager indicated that an imager of a size and weight commensurate with human transportation between platforms could be built which would give a reasonable image resolution within a minute, for a relatively weak source at a typical road-to-building distance. Over the first couple of years of running the project, more detailed simulations were performed confirming this result, and test-bench studies were performed to validate the simulations. Around the third year of the project, it became clear a) that potential target end-users would not have the financial resources to procure the kind of imager which could be developed using all of the project funds and b) that two different design philosophies (bar, and pixel) were equally promising, with different risk profiles. Therefore the decision was taken to move forward with two less-expensive prototypes, and also to move some funding from equipment into salary to retain a talented research associate for an additional year. In the final years, the two prototypes were manufactured, assembled and tested. At the conclusion of this project, two laboratory prototypes exist, both of which are capable of imaging a 10 mCi source 40 m distant in a 45° x 45° field of view to better than a degree image resolution in under a minute. The project scientists continue to work together conducting research with the prototypes, and seeking a way forward toward eventual commercialization.

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[20] Annex A: The Charter, Project Charter CRTI 07-0193RD, A Compton Gamma Imager for Criminal and National Security Investigation, to the Memorandum of Understanding concerning the Chemical, Biological, Radiological and Nuclear, Research and Technology Initiative, Wed Nov 24th, 2010 Ver 3.0, last signature Feb 8, 2011

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Annex A Project Team

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Annex B PROJECT PERFORMANCE SUMMARY

B.1 Technical Performance Summary

B.1.1 Technology Readiness Level of Deliverable

This project advanced the Technology Readiness Level (TRL) of a gamma imager for use by Canadian security and response personnel from TRL 3 to TRL 5. At the start of the project, the basic theory of Compton imaging was well-known, and Compton imagers were well established in particle astrophysics, but extensive research and investigation indicated that there were no suitable Compton imagers deployed by security teams anywhere in the world. As of the end of the project, two Compton imagers designed for safety and security use have been validated in a laboratory environment. Moreover – the performance of the imagers has been validated under some relevant operational conditions such as production of an image in a timely manner, and presence of multiple sources in the field of view.

B.1.2 Estimated Time to Reach TRL 7 Maturity

To reach TRL 7, demonstration in an operational environment, the imagers will have to be ruggedized, as discussed in 6.2.2. To achieve this, an agreement would have to be made with an engineering or commercial organization, and in the absence of significant government funding, a market analysis would have to be performed to justify the resource commitment of a commercial organization. The project partners are scientists without the necessary training in commercial operations to make a firm estimate of the time involved, but would guess that one to two years would be necessary for these advances.

B.1.3 Advantages Over Existing/Competing Technologies

The mobile gamma survey systems which are currently the world-wide standard for support to security operations are based on large-volume non-directional NaI(Tl) spectrometers. There are a few directional gamma spectrometers which have become commercially available over the past few years. These do represent a significant improvement over non-directional systems, but are not in wide-spread use[1 2]. The Compton imager represents a major step forward again from the directional systems, constraining two of the degrees of freedom of the source position, and allowing for the resolution of multiple, and of distributed sources.

During the course of this project, the United States Domestic Nuclear Detection Office (DNDO) issued a large call for project proposals to develop Stand-off Radiation Detection Systems

[1] Khan, M.S., "Source localization using a directional gamma-ray spectrometer", M.Sc. Thesis, Ottawa Carleton Institute for Physics, Carleton University, Ottawa, Canada, Nov 2012
[2] Larsson, C.L., Djeffal, S., "Development of a directional gamma ray probe", IEEE Nuclear Science Symposium Conference Record, Vol 1, p 16 – 18, 2005

(SORDS)[3]. Over $10 M of funding was provided to each of a number of institutions to develop large-volume mobile gamma imaging systems. The SORDS program was complete within the time-frame of this project. One member of the project team attended a demonstration of these system capabilities[4]. To a large extent, the developed systems consisted of commercial off-the-shelf components mounted inside dedicated vans or trailers. Three of the four viewed did not feature Compton imaging technology, but older coded-aperture technology which is less effective at high energies, and which involves carrying large quantities of dead (insensitive to gamma rays) material. One of the designs, however, was quite innovative and did make use of Compton imaging, along with the coded-aperture and directional modalities[5]. It is, however, the opinion of this project team that our prototypes which followed a more extensive and consultative design period are much more suited to Canadian operators. The tri-model imager, for example, would cost many times the cost of one of our imagers. It is also extremely large and fixed inside a particular cube-van. This is counter to the philosophy employed by the Canadian nuclear emergency response teams to provide coverage over a very wide country on a limited budget by utilizing instruments which can be transported and deployed from a variety of platforms.

B.2 Schedule Performance Summary

Table 1: Schedule Performance Summary

Milestone	**Anticipated Completion**	**Actual Completion**
Project Approval	Feb 2008	Feb 2008
Charter signed	n/a	Sep 17, 2008
McGill Contract Award	Aug 2008	Dec 2008
First simple back-projection image from data	Jul 2009	two-pixel: Feb 2009
Kick-off meeting	n/a	Feb 2009
First high resolution image from data	Aug 2009	two-pixel: Feb 2009 partial prototypes: Oct 2010
Finalize prototype design	Jan 2010	decision to pursue two designs: Jan 2010 designs complete: Jul 2010
Submit design publication	Mar 2010	Mar 2010
Prototype hardware complete	Aug 2010	bar design: Nov 2010 pixel design: Mar 2011

[3] Department of Homeland Security, Domestic Nuclear Detection Office, Broad Agency Announcement 07-01, Advanced Technology Demonstration, Stand-Off Radiation Detection Systems, Oct 4, 2006
[4] SORDS instruments demonstration, Savannah River Nuclear Lab, Jan 14, 2009
[5] Wakeford, D., et al, "The SORDS trimodal imager detector arrays", Proc. SPIE 7310, 73100D, 2009

First image from data using prototype	Feb 2011	mini prototypes: Oct 2010 demo units: Jun 2011 full bar prototype: Dec 2011 full pixel prototype: Aug 2012
Submit publication on characterization of prototype	June 2011	pixel demo unit: Nov 2011, journal bar demo unit: Nov 2011, conference
First demonstration of prototype	May 2012	Nov 2012
Demonstration in realistic scenario	Jul 2012	multiple sources: Nov 2012 outdoor: beyond scope of project
Project Close-out Meeting	Aug 2012	Apr 2013
Project Close-out Report	Dec 2012	Apr 2013
Peer Review – Summer Symposium	Jun 2013	n/a

Heavier than anticipated involvement in the security operation for the Vancouver 2010 Olympic games, affected two of the scientists working on the pixel imager. As well, emergency response to the Fukushima nuclear power accident completely interrupted the work of all three scientists working on the pixel imager for a period of months. For these reasons, and due to the complexity of assembly of the pixel imager, the pixel imager was not ready to demonstrate until Nov 2012. The bar imager was actually ready to demonstrate on schedule, in May 2012, however it was decided to delay demonstration of the bar imager so that both could be presented at the same time, beginning in Nov 2012.

A range of scenarios were chosen for the demonstration which progressed toward more realism, including finding sources which were hidden from view of the operators, and distinguishing more than one isotope in the field of view. It was decided, however, that conducting outdoor demonstrations with a realistic scenario was beyond the scope of the current project.

The project close-out meeting was originally mistakenly scheduled to take place before the completion of the project close-out report. The project close-out report date is thus a more relevant milestone in the project schedule review.

The project did submit an abstract to the summer symposium for the final peer-review milestone, on time, however the Centre for Security Science has cancelled this symposium and this requirement.

B.3 Cost Performance Summary

The first signed Charter for the project was Version 1.9, August 13th, 2008. The revision which resulted in Charter Version 2.0, March 11th, 2009, allowed for $30,500.00 of equipment funding allocated to McGill to roll forward from fiscal year 2008/2009 into fiscal year 2009/2010. This compensated for the late start of McGill into the project due to the lengthy contracting process.

In fiscal year 2009/2010, following a poll on projected available funding from intended end-users, it was decided to build less-expensive prototypes, and also to continue to benefit from the work of a research associate at McGill. Therefore, Charter Version 3.0, November 24th, 2010, allowed for a roll forward of $125,000.00 of equipment funds, and conversion of this funding type into salary.

Table 2 presents actual expenditures against the projected funding as realised in the final Charter version, Version 3.0.

Table 2: Cash Flow Summary

Project Participant	**Fiscal Year**	**CRTI Funds Charter V. 3.0**	**Actual Expenditures**
Definition Funds	2008/09	0.00	0.00
Natural Resources Canada	2008/09	14,454.00	15,370.00
(Lead Federal Department)	2009/10	22,648.00	22,648.00
	2010/11	180,648.00	237,222.14
	2011/12	15,648.00	15,648.00
	2012/13	0.00	1,872.47
National Research Council	2008/09	22,000.00	22,000.00
	2009/10	43,250.00	43,250.00
	2010/11	180,000.00	180,000.00
	2011/12	11,250.00	11,250.00
	2012/13	0.00	0.00
McGill	2008/09	55,357.50	54,441.00
	2009/10	197,215.00	197,215.00
	2010/11	413,215.00	356,640.86

	2011/12	219,715.00	219,715.00
	2012/13	49,857.50	48,003.03
RCMP, Public Safety, Toronto Police, CBSA (Operational partners)	2008/09	0.00	0.00
	2009/10	0.00	0.00
	2010/11	0.00	0.00
	2011/12	0.00	0.00
	2012/13	0.00	0.00
Total by Fiscal Year	2008/09	91,811.50	91,811.50
	2009/10	263,113.00	263,113.00
	2010/11	773,863.00	773,863.00
	2011/12	246,613.00	246,613.00
	2012/13	49,857.50	49,875.50
Grand Total		1,425,258.00	1,425,276.00

The project plan originally called for a single prototype to be assembled largely at McGill. As we progressed with building two less-expensive prototypes – some equipment funding allocated to McGill was actually spent by NRCan on parts for the pixel prototype.

In fiscal year 2012/2013 an accounting error meant that an extra $18.00 was accidentally transferred from CSSP to NRCan. A decision was taken by NRCan that the value of the time which would be expended to return this money to CSSP would greatly exceed the sum in question, and therefore the extra money was spent by NRCan on equipment for the project.

Table 3 presents the in-kind effort as projected in Charter Version 3.0, and as realized.

Table 3: In-kind Effort Summary

Project Participant	**Fiscal Year**	**In-kind Effort Charter V. 3.0**	**Actual In-kind Effort**
Definition Funds	2008/09	200.00	
Natural Resources Canada (Lead Federal Department)	2008/09	90,000.00	131,255.00
	2009/10	177,500.00	205,327.52
	2010/11	175,000.00	143,752.00
	2011/12	177,500.00	134,706.00
	2012/13	90,000.00	96,019.00

National Research Council	2008/09	41,735.00	82,750.00
	2009/10	83,470.00	110,578.00
	2010/11	83,470.00	112,050.00
	2011/12	83,470.00	113,555.55
	2012/13	41,735.00	85,166.67
McGill	2008/09	60,500.00	121,000.00
	2009/10	121,000.00	121,000.00
	2010/11	121,000.00	121,000.00
	2011/12	121,000.00	121,000.00
	2012/13	60,500.00	90,750.00
RCMP, Public Safety,	2008/09	3,000.00	3,000.00
Toronto Police, CBSA	2009/10	3,000.00	240.00
(Operational partners)	2010/11	0.00	3,500.00
	2011/12	3,000.00	0.00
	2012/13	0.00	4,000.00
Total by Fiscal Year	2008/09	195,435.00	338,005.00
	2009/10	384,970.00	437,145.52
	2010/11	379,470.00	380,302.00
	2011/12	384,970.00	369,261.55
	2012/13	192,235.00	275,935.67
Grand Total		1,537,080.00	1,800,649.74

Heavy operational responsibilities in fiscal years 2010/11 and 2011/12 meant that NRCan was unable to provide the number of man-hours originally foreseen. Fortunately, NRC was able to provide additional hours on the scientific research and to keep the project progressing at the expected level of commitment.

Operational partners provided feedback during the design phase of the project, and participated in the project demonstrations, which were conducted in later fiscal years than originally anticipated.

Additional unforeseen in-kind expenditure occurred in fiscal year 2008/2009 before the project was anticipated to start, and in fiscal year 2012/2013, after the project work had been anticipated to end.

Annex C Publications and Presentations

C.1 Journal Publications

L.E.Sinclair, D.S.Hanna, A.M.L.MacLeod, P.R.B.Saull, “Simulations of a Scintillator Compton Gamma Imager for Safety and Security”, IEEE Trans.Nucl.Sci. Vol 56, p1262-1269, 2009

A.MacLeod, P.Boyle, D.Hanna, P.Saull, H.Seywerd, L.Sinclair “All-Scintillator Compton Gamma Imager”, Physics in Canada, Vol 65, No 3, Apr-Jun 2009

A.Macleod, P.Boyle, D.Hanna, P.Saull, H.Seywerd, L.Sinclair, “Development of a Compton Gamma-Ray Imager”, Physics in Canada, Vol 67, No 3, p191-193, 2011

P.R.B.Saull, L.E.Sinclair, H.C.J.Seywerd, D.S.Hanna, P.J.Boyle, A.M.L.MacLeod, "First demonstration of a Compton gamma imager based on silicon photomultipliers", Nucl. Instr. and Meth. A. Vol 679, p89-96, 2012

C.2 Conference Proceedings

A.M.L.MacLeod, D.S.Hanna, P.R.B.Saull, H.C.J.Seywerd, L.E.Sinclair, “Design Studies for an All-Scintillator Compton Telescope”, Nuclear Science Symposium Conference Record, Dresden, Germany, p1198 – 1201, 2008

P.R.B.Saull, L.E.Sinclair, H.C.J.Seywerd, P.J.Boyle, A.M.L.MacLeod and D.S.Hanna, “A two-pixel Compton Imager”, Proc. SPIE 7665, p76651E – 76651E-11, 2010

A.M.L.MacLeod, P.J.Boyle, P.R.B.Saull, D.S.Hanna, L.E.Sinclair and H.C.J.Seywerd, "Development of a Compton Imager based on Scintillator Bars", Nuclear Science Symposium Conference Record, Valencia, Spain, art. no. 6154536 p444 – 449, 2011

P.J.Boyle, D.S.Hanna, A.M.L.MacLeod, L.E.Sinclair, H.C.J.Seywerd, P.R.B.Saull, "Optimization of pulse-height sharing for use below 150 keV in long bars of NaI(Tl)", Nuclear Science Symposium Conference Record, Valencia, art. no 6154535, p440 – 443, 2011

C.3 Presentations

L.E.Sinclair, D.S.Hanna, A.M.L.MacLeod, P.R.B.Saull, “Gamma Imaging for Safety and Security”, poster presented at 2008 Symposium on Radiation Measurements and Applications, Berkeley USA, Jun 2 – 5, 2008

A.M.L.MacLeod, “Compton Gamma-Ray Imager Design”, CAM congress, Acapulco, Oct 2009

L.E.Sinclair, “Survey and Imaging Techniques for the Localization of Radioactive Threat Material: KEGS Ottawa Seminar, Jan 19, 2010

L.E.Sinclair, “Long Range Detection of Radioactive Threat Material”, Carleton University Seminar, Mar 2010

P.J.Boyle, "The Development of a Gamma-ray Imaging Camera", Dept. of Medical Physics Seminar, Montreal General Hospital, Jun 2010

L.E.Sinclair, “Long Range Detection of Radioactive Threat Material”, McMaster University Seminar, Sep 2010

P.R.B.Saull, “A Compton Gamma Imager for Safety and Security”, Ottawa Medical Physics Institute, Carleton University, Ottawa, Sep 2012

C.4 Public Dissemination of Science

NRC Highlights – Detecting deadly Radioactive Material, Feb 2010
http://www.nrc-cnrc.gc.ca/eng/news/nrc/2010/02/01/radioactive-detection.html

C.5 Awards

Canadian Association of Physicists Congress “Best Student Oral Presentation: 3rd Place” awarded to Audrey MacLeod, 2009

Canadian Association of Physicists Congress “Best Student Oral Presentation: 3rd Place” awarded to Audrey MacLeod, 2011

C.6 Academic

A.M.L.MacLeod, McGill University Ph.D. thesis in preparation

List of symbols/abbreviations/acronyms/initialisms

CBRNE	Chemical Biological Radiological/Nuclear and Explosives
CRTI	CBRNE Research and Technology Initiative
CSSP	Canadian Safety and Security Program
NRCan	Natural Resources Canada
NRC	National Research Council
PMT	PhotoMultiplier Tube
SiPM	Silicon PhotoMultiplier
SPMArray	A 1.35 cm x 1.35 cm array of silicon photomultipliers, with signals summed into one readout pulse.
GAIA	GAmma Imaging Analysis
RMS	Root Mean Square
CSSP	Canadian Safety and Security Program
DRDC	Defence Research and Development Canada
NER	Nuclear Emergency Response
CsI(Tl)	thallium-doped caesium iodide
NaI(Tl)	thallium-doped sodium iodide
TRL	Technology Readiness Level